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Soil organic carbon fractions in oil palm management systems

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Abstract. Conversion of deforested areas into oil palm plantation has been suggested as a means to improve soil quality and carbon sequestration capacity in forest margin areas. Soil organic carbon fractions, such as particulate organic carbon is the most sensitive indicator in improving soil organic matter and soil quality. We determined particulate organic matter - carbon (POM-C) and mineral associated carbon (MAC) in Bengkulu and West Java Provinces Indonesia. The study areas were grain crop fields, secondary forest, 5 yr-oil palm plantation, 10 yr-oil palm plantation, 15 yr-oil palm plantation and 25 yr-oil palm plantation. Soil organic carbon fraction magnitudes varied in the surface of 0 to 30 cm of grain crop fields, secondary forest and oil palm plantations. Twenty five year- oil palm plantation provided the largest total organic carbon, while 5 yr-oil palm plantation and grain crop fields contained similar amount of total organic C. Both POM-C and MAC fractions were increased in the plantation sites with oil palm trees and secondary forest compared to the grain crop fields. The plantation sites had a larger POM-C content than grain crop fields, but the increase of POM-C was limited to the surface of 0 to 10 cm of soil. Carbon stock in 0-30 cm under oil palm plantations were reduced up to 20% compared to secondary forests and 28% compared to rubber plantations in Bengkulu and West Java Provinces. On average, converting forest to plantations led to a loss of 10 Mg C/ha after about 10 years of conversion. However, the C stock in the subsoil was similar under the forest and the plantations in Bengkulu. Further, limited C input from litter would eventually cause more losses of SOC in oil palm plantations compared to rubber plantations. In conclusion, investigating the deeper profiles and soil erosion may be an important tool to unfold the trends of soil organic carbon fraction dynamics and magnitudes after the conversion of natural ecosystems to intensive plantations.

Keywords: carbon sequestration, crop field, deforestation, particulate organic matter, plantation

1. Introduction

Oil palm is a main crop in the tropics, and its rapid spread has essential implications for global climate change [1]. Oil palm plantations cover more than 16 million ha and the area is increasing at the rate of 400.000 ha/y[2]. From the perspective of global climate change, carbon sequestration and biodiversity, it is favorable that further expansion occurs in non-forested areas rather than forested areas, which sequester 36-60% carbon in the ecosystem [3, 4, 5].

Previous studies have shown that the soil organic carbon (SOC) stocks in tropical areas decline when they are cultivated [6, 2], but that may not necessarily be the case with oil palm. It was reported that there was an overall increase in SOC level with plantation age, with SOC increasing under frond piles and decreasing in harvest paths [7]. It was observed that replanted oil palm plantations of various ages and found no effect of plantation age on SOC stocks [8]. In addition, it was reported stable SOC stocks in peach palm [*Bactris gasipaes* (Kunth)] plantations over 7 years [9]. On the other hand, It was identified that stable SOC stocks in oil palm soils compared to forest soils, and increasing SOC spatial variability as organic C was concentrated around the trees as root materials [10]. Research in peat soils showed that large amounts of C were released to the atmosphere following conversion to oil palm, due to the lowering of the water table by the installation of drainage systems [5, 8]. During oil palm cultivation, clearing as well as slash-burn practices remove the primary source of litter, thus leads to a decline in organic matter supply in the soil [11, 12]. it was measured an increase of SOC content with plantation age where the previous land cover had been secondary forest [13].

In temperate Europe and North America, revegetation and forest fallow had restored soil conditions and improved land productivity once degraded by cultivation [14]. The role of amelioration on organic matter supplies to degraded soils has been demonstrated both in the young and in the old temperate zones, highly weathered soils of the tropics [15, 16]. However, the effects of amelioration on soil organic carbon fractions are poorly understood. The investigation of the physical fractionation of soil organic matter, which is biologically active within the soil environment, is relevant to assess the impact of revegetation on soil quality [17]. Soil organic C fractions have a good relationship to critical soil functions like productivity, erodibility or transforming potential pollutants [18, 19]. Particulate organic matter (POM) is one of a biologically-active form of soil organic matter that is isolated using physical fractionation [17, 18]. Particulate organic matter is considered to be a sensitive indicator of soil quality because it responds rapidly and selectively to changes in land use, soil management, and ecosystems [19 , 21, 22]. It appears to be more sensitive than the total organic carbon [23]. This may be caused by differential decomposition rates under various ecosystems, management, and climatic conditions [24, 25]. In Australia, soil organic matter decreased when pasture was converted to crop production, with 70% of the loss of organic carbon comes from particulate organic carbon [26]. it was reported that 4 and 10 y of no-tillage increased particulate organic matter by 19 and 37%, respectively, compared to tillage practices [27]. Besides, there was no significant differences on soil organic carbon between pasture and plantation, but particulate organic carbon was higher in plantation soils (75%) than under pasture (62%) [28]. This reflected higher coarser organic inputs under plantations.

The amount of particulate organic carbon only accumulated up to 5 cm depth under tillage systems [22, 23, 29]. It was reported that particulate organic carbon was accumulated up to 30 cm under various urban landscapes [30]. It was found that carbon contents in the topsoil under oil palm and rubber plantations were strongly reduced up to 70% and 62%, respectively, following 15 years of forest conversion in Sumatra [31]. The decrease was lower under extensive rubber plantations (41%). On average, converting forest to plantations led to a loss of 10 Mg C/ha. The C content in the subsoil was similar under the forest and the plantations.

Forest conversion to plantation reduces the C input from the above- and belowground litters [29]. The decomposition of SOC is enhanced by nutrient release from the dead or burnt biomass and by the labile organic matter released from disturbed soil aggregates during conversion to plantations [24]. Soil erosion is strongly increased when the forest is converted to agricultural land [32], especially when the protective soil cover (litter layer and canopy) is removed [28]. These published data

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provides information that the dynamics of SOC content can be studied via quantifying the SOC fractions at various plantation age. In summary, this study was designed (1) to examine trends in soil organic matter pools and to quantify the sampling depth effect on the changes in soil organic matter C and particulate organic carbon, following conversion of lowland forest to plantations and (2) to investigate dynamics of C stocks in different estates and study sites.

2. Materials and Methods

Industrial oil palm plantations were selected to study the changes of SOC fractions at various plantation ages, all located in Sumatra (Bengkulu Province) and Java (West Java) islands. The area has a humid tropical climate; annual rainfall was between 1500-2800 mm. The land ranges from 75 to 750 m above sea levels. All the soils are Typic Paleudult, containing 49-68% of clay, 20-28% of sand, 11-24% of silt, and 3-18% base saturation. The soil had a bulk density of 1.1 to 1.4 Mg m^{-3}, P-Bray 1 of 2-3.5 ppm, K_2O of 50-220 ppm, cation exchange capacity of 1.07 – 2.05 meq per 100 g and pH in the water of 4.0 - 4.5. Predominant trees in the secondary forests were *Ficus septica, Ficus ampelas, Ficus variegate*, and *Hibiscus* spp. Grain crops were corn, soybean, and upland rice.

Soil samples were collected from each field at a depth of 0-10 and 10- 30 cm. From each field of the 400 m^2 plots, disturbed soil samples were taken from five randomly distributed sampling points. In the laboratory, the disturbed and undisturbed soil samples were freed from visible remnants of roots, air-dried, sieved (< 2 mm), and finally dried at 40^{o}C for five days. For basic chemical analyses, samples from each plot were pooled. Undisturbed soil samples were used to determine bulk density to calculate the C stock from each field. Usually, rubber and oil palm plantations were established by burning the land after timber extraction. Soils were not tilled, but no measures against erosion were taken. The understory vegetation was absent or sparse, leaving the soil mostly bare in oil palm plantations.

The soil sample for particulate organic carbon analysis was dispersed with 150 ml of 5-g L^{-1} sodium hexametaphosphate and shaken for 18 hours on a reciprocal shaker. The dispersed soil samples were passed through a 53 - µm sieve and rinsed thoroughly with water until the rinsate was clear. The material retained on the sieves was backwashed into small aluminum pans and dried at 70^{o}C for 48 hours. The longer time was needed to evaporate the water accumulated during rinsing. The weight of each dried sample was recorded to three decimal places. The dried fraction samples were ground in a ball mill to pass through a 250 - µm and then analyzed for carbon using a muffle furnace. Mineral associated organic carbon was calculated as the difference between total soil organic matter and the particulate organic carbon [18]. The data were statistically analyzed using a one-way analysis of variance and Least Significant Differences to determine differences between means.

3. Results and Discussions

This study was not designed to investigate the changes in the stocks of soil organic matter in the whole profile of the Sumatra or Java's soils resulting from land conversion to oil palm plantation. Therefore, the data presented are based on concentrations in the depth interval of 0 to 10 cm and 10 to 30 cm. In fact, changes in the concentration, the distribution, and the composition of soil organic matter may occur at first and most pronounced in the surface soil. In general, only soil organic matter in the topsoil or A horizons can be in equilibrium with the present vegetation [33].

3.1.Carbon and nitrogen in whole soils

Carbon and nitrogen exhibited the lowest concentrations in the soil under grain crop fields and 5yr-oil palm plantations (Table 1). The lower soil organic matter content at grain crop fields compared to the secondary forest was most probably a result of the intensive cropping systems without additional input of fertilizer and burning practices. Rapid exhaustion of soil organic matter is frequently observed after land clearing for agricultural use [22, 34]. Soils in 5y-oil palm plantation showed slightly higher C concentration than the soil under grain crop fields. After 15 y, oil palm plantations provided high C content exceeding that observed in soil under secondary forest. Besides the different vegetation, spatial variability may be also responsible for this data. Oil palm plantations showed more uniform soil surface due to the routine maintenance compare to secondary forest and grain crop fields. However, it is well accepted that the presence of secondary forest vegetation and the long-term revegetation restores soil organic matter pools [17]. In tropical southeastern Mexico, a recovery of the C content to a level of primary forest occurred after 50 years of secondary forest succession [35]. In their study, the decline of the C content was more pronounced due to the longer duration of cropping (5-y old crop). The C/N ratio was relatively constant under grain crop field, secondary forest, and 5-y old oil palm plantation (Table 1), providing a first indication that the quality of soil organic matter was less affected during succession and short-term amelioration. However, increasing C/N ratio after 15 y of oil palm plantation (Table 1) indicated that the quality and quantity of soil organic matter were affected by the length of establishment. This also suggests that a larger increase in C than in N after 15 yr of oil palm production. It was obtained similar results for soils in Papua New Guinea [32].

The altitude of the sampling sites decreased from secondary forest (150-200 m) to oil palm plantation (75100 m), with smaller differences between oil palm plantations and grain crop field (50-75 m). Lower temperatures at higher altitudes increase the accumulation of organic matter. The difference in altitude may have an effect on the differences in organic matter of the topsoil of secondary forest and other types of land use. It was reported that the organic C in the topsoil increased by a factor of 1.04 per 100 m increase in altitude in Indonesia when the types of soil and land use are identical [36]. In this study, the organic matter had not returned to the initial values even after establishing with oil palm plantation for 5 years. However, total C and N in the depth of 10 to 30 cm tended to be greater in all the plantation soils (Table 1), indicating the importance of oil palm trees to improve organic matter supplies compared to secondary forest.

Table 1. Carbon, nitrogen, and C/N ratios from Sumatra and West Java soils; n = 6

Vegetation	Carbon (g kg^{-1})	Nitrogen (g kg^{-1})	C/N
		Depth 0-10 cm	
Grain Crop field	21.57a	2.52a	8.55b
Secondary forest	31.44b	3.64b	8.63a
5y- Oil Palm plantation	25.25a	2.72a	9.28b
15y- Oil Palm plantation	58.96c	3.88b	15.19d
20y- Oil Palm plantation	62.23c	3.76b	16.55d
25y-Oil Palm plantation	76.90d	4.99c	15.41c
		Depth 10-30 cm	
Grain Crop field	11.82a	0.88a	13.43c
Secondary forest	18.58b	2.54b	7.31a
5yr- Oil Palm plantation	12.20a	1.58a	7.72b
15yr- Oil Palm plantation	38.25c	2.78b	13.76d
20yr- Oil Palm plantation	36.70c	2.98b	12.32c
25yr-Oil Palm plantation	54.60d	3.62c	15.08d

[a] Values in the same column followed by the same letter are not significantly different at $p < 0.05$ according to the Least Significant Differences test.

3.2. Particulate organic matter carbon (POM-C)

At all depth, soil management systems significantly affected the amount of particulate organic matter-C (POM-C) and mineral-associated C (MAC) (Table 2). Particulate organic matter C comprised 10 to 21% of the total organic C in the surface 0 to 10 cm of the oil palm plantation sites and secondary forest, but only 6-8 % of total organic C of the grain crop fields (Table 2). Particulate organic matter-

C content in the grain crop soils, as a fraction of the total organic C, decreased rapidly with the depth ranging from 8.50% to 6.60% of the total organic C in the 10 to 30 cm depth interval. Particulate organic matter-C as a fraction of total organic C stayed about the same in the secondary forest in depth 10 to 30 cm depth interval.

Table 2. Particulate organic matter carbon (POM-C), mineral-associated C (MAC) and the ratio of particulate organic matter to soil organic matter (POM/SOM) from Sumatra and West Java soils

Vegetation	POM-C (g kg^{-1})	MAC(g kg^{-1})	POM/SOM
Depth 0-10 cm			
Grain Crop field	1.89a	19.68a	8.76a
Secondary forest	5.79b	25.65a	18.42c
5yr- Oil Palm plantation	2.64a	22.61a	10.46a
15yr- Oil Palm plantation	8.98c	49.98b	15.23b
20yr- Oil Palm plantation	9.67c	52.56b	15.54b
25yr-Oil Palm plantation	15.95d	60.95c	20.74d
Depth 10-30 cm			
Grain Crop field	0.78a	11.04a	6.60b
Secondary forest	3.86b	14.72b	18.61a
5yr- Oil Palm plantation	0.95a	11.25a	20.78a
15yr- Oil Palm plantation	6.98c	31.27c	18.24a
20yr- Oil Palm plantation	6.67c	30.03c	17.43a
25yr-Oil Palm plantation	10.99d	43.61d	20.13a

[a] Values in the same column followed by the same letter are not significantly different at $p < 0.05$ according to the Least Significant Differences test, n=6

The establishment of oil palm in Indonesian's soils resulted in a quick replenishment of the POM, indicating high biomass production after 15 years. After 5 years, the POM-C represented 18% of the whole soil C and even exceeded the size of the respective SOM pool under the secondary forest. This may have resulted from differences in substrate variability. However, regression analysis relating POC to the length of time in oil palm trees was not significant. It was suggested that changes in lignin and carbohydrates within the fractions were primarily a function of changes of the SOM content among the land use types [31]. In addition, they mentioned that the behavior of SOM is primarily controlled by its physical location within the soil matrix, and the land use influences the C balance in POM primarily.

Mineral-associated C (MAC) was also increased in the oil palm plantation sites after 15 years compared to secondary forest soils. At a depth of 10 to 30 cm, MAC reduced up to 50% compared to 0 to 10 cm. As a fraction of total organic C with a given depth, MAC increased in the oil palm plantation soils as the amount of POM-C increased.

Establishing oil palm trees increased the size of both POM-C and MAC, but the POM-C fraction was increased more than MAC pool, especially in the soil surface. Previous research indicated that much of the POM-C was retained in the anaerobic portion of larger soil aggregates (38) (39). Cultivation disrupted soil aggregates and the POM-C exposed to aerobic conditions, leading to oxidation of the organic C. As the POM-C is decomposed, it enters the mineral associated organic C fraction. This explained why the POM-C is more influenced by land management systems than MAC (25). It was reported that POM-C was lost more rapidly than other C fractions when pasture was cultivated [26]. The fastest change in POM-C occurred within the first to four years, with subsequent losses occurring at a slower rate. In this study, 50 years of conventional tillage and burning of stubble resulted in 42% of POM-C in the surface 10 cm. In the current study, POM-C was also reduced in the 10 to 30 cm depth interval in all sites with a range from 6 to 20% of POM-C to total organic C.

In general, POM-C was greater in the plantation sites than in grain crop fields. Most of the POM-C accumulation occurred after 5 years of oil palm plantation. This is similar to other studies [31, 32]. The POM-C accumulation was assumed to be derived from recent root and residue additions [18]. It was found that 75% of the soil C increase after 4 years of pasture establishment was in POM-C fraction [26]. The rapid increase of POM-C accumulation in soil may approach a new plateau level relatively fast. This is the reason for no significant of regression analysis between POM-C content relative to the time-in-tree establishment for this study. In contrast with this study, it was found that there was no significant difference in total organic C between pasture and *Eucalyptus globulus* plantation, but POC was higher in plantation soils compared to pasture [28].

3.3.Carbon Stocks

Carbon stocks losses in Bengkulu and West Java in the 0 –30 cm layer showed the same decrease pattern as the C content (Table 3). The C stock reduction in plantations was significant down to 30 cm depth, but not when deeper layers were included. In West Java, however, there were no significant differences in C stocks in the top 0-10 cm between oil palm plantations and secondary forests. Plantations had much less C stocks in the top 30 cm in Bengkulu (33.90 Mg C/ha) than in West Java (44.15 Mg C/ha). This relation reflected both the higher SOC losses after conversion of forest to plantations in Bengkulu and the higher C content in the West Java subsoil.

Table 3. Soil Carbon Stocks (Mg C/ha) in 4 land-use types of Bengkulu and West Java Provinces

Land use	Bengkulu		West Java	
	0-10 cm	10-30 cm	0-10 cm	10-30 cm
Oil Palm plantations	25.3 (2.5) a	42.5 (3.2) a	28.5 (3.6) a	55.8 (6.7) a
Rubber plantations	24.6(1.9) a	45.2 (1.5) a	42.6 (4.2) b	83.2 (12.3) c
Secondary forests	36.8 (3.2) b	55.6 (4.2) a	32.2 (3.4) a	62.8 (4.3) b
Agroforestry systems	26.9 (3.4) a	48.4 (3.6) a	34.5 (6.8) a	72.6 (6.6) b

*Values represent means (SE) (n = 6).
‡Means followed by different letters within a column differ significantly (t-test at P < 0.05)

4. Conclusions and recommendations

Soil organic carbon fractions varied in the surface of 0 to 30 cm of grain crop fields, secondary forest, and oil palm plantations. Twenty-five years of oil palm plantation provide the largest total organic C, while 5 yr-oil palm plantation and grain crop fields contained a similar amount of total organic C. Both POM-C and MAC pools were increased in the plantation sites with oil palm trees and secondary forest compared to 5-y oil palm plantation and grain crop fields. The oil palm plantation sites had a larger POM-C content than grain crop soils, but the increase in POM-C was limited to the surface of 0 to 10 cm of soil. In this study, significant trends in soil organic C fractions over time from 5 to 25 years of oil palm plantation were observed. Plantations had much less C stocks in the top 30 cm in Bengkulu (33.90 Mg C/ha) than in West Java (44.15 Mg C/ha). This relation reflected both the higher SOC losses after the conversion of forest to plantations in Bengkulu and the higher C content in the West Java subsoil.

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